Tropical moist dynamical theory from AIRS and TRMM

Background: Convective quasi-equilibrium

1. Vertical T structure (AIRS)
2. Onset of strong convection regime as a continuous phase transition with critical phenomena (TRMM)

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Climate Systems Interactions Group

Background: Convective Quasi-equilibrium (QE)

Manabe et al 1965; Arakawa & Schubert 1974;
Moorthi & Suarez 1992; Randall & Pan 1993; …

- Posit that bulk effects of convection tend to establish statistical equilibrium among buoyancy-related fields – temperature T & moisture q
- Slow driving (moisture convergence & evaporation, radiative cooling, …) by large scales generates conditional instability
- Fast removal of buoyancy by moist convective up/down-drafts
- Above onset threshold, strong convection/precip. increase to keep system close to onset
- Convection tends to constrain vertical structure of T, q fields and T-q relationships

Quasi-equilibrium (QE) moist convection schemes (cont.)

e.g., **Smoothly posed convective adjustment**

Convective heating: (Betts 1986; Betts & Miller 1986)

$$Q_c = (T^c - T)/\tau_c \qquad \text{(if vert int > 0)}$$

Convective moisture sink (vertical integral=Precip):

$$-Q_q = (q - q^c)/\tau_c \qquad \text{(if vert int > 0)}$$

τ_c time scale of convective adjustment

T_c convective temp. profile; may interact with atm boundary layer (ABL) moist static energy, tropospheric moisture

T^c ~ moist adiabat if neglect entrainment,…

$q^c = \alpha q_{sat}(T)$ convective moisture closure

T^c incl. ABL adjustment by downdrafts to satisfy energy constraint: vertically integrated $(Q_c+Q_q)=0$

Later: vert int $(q)=w$, and we'll look for w_c

1. Tropical vertical T structure

C. Holloway & J. D. Neelin, in prep for J. Atmos. Sci.

- Background: implications of convective quasi-equilibrium
- QE postulates **deep convection constrains vertical structure of temperature** through troposphere near convection
- If so, **gives vertical str. of baroclinic geopotential variations, wind**
- **On what space/time scales does this hold well?**
- **Approx. moist adiabat? Relation to ABL? Top?**

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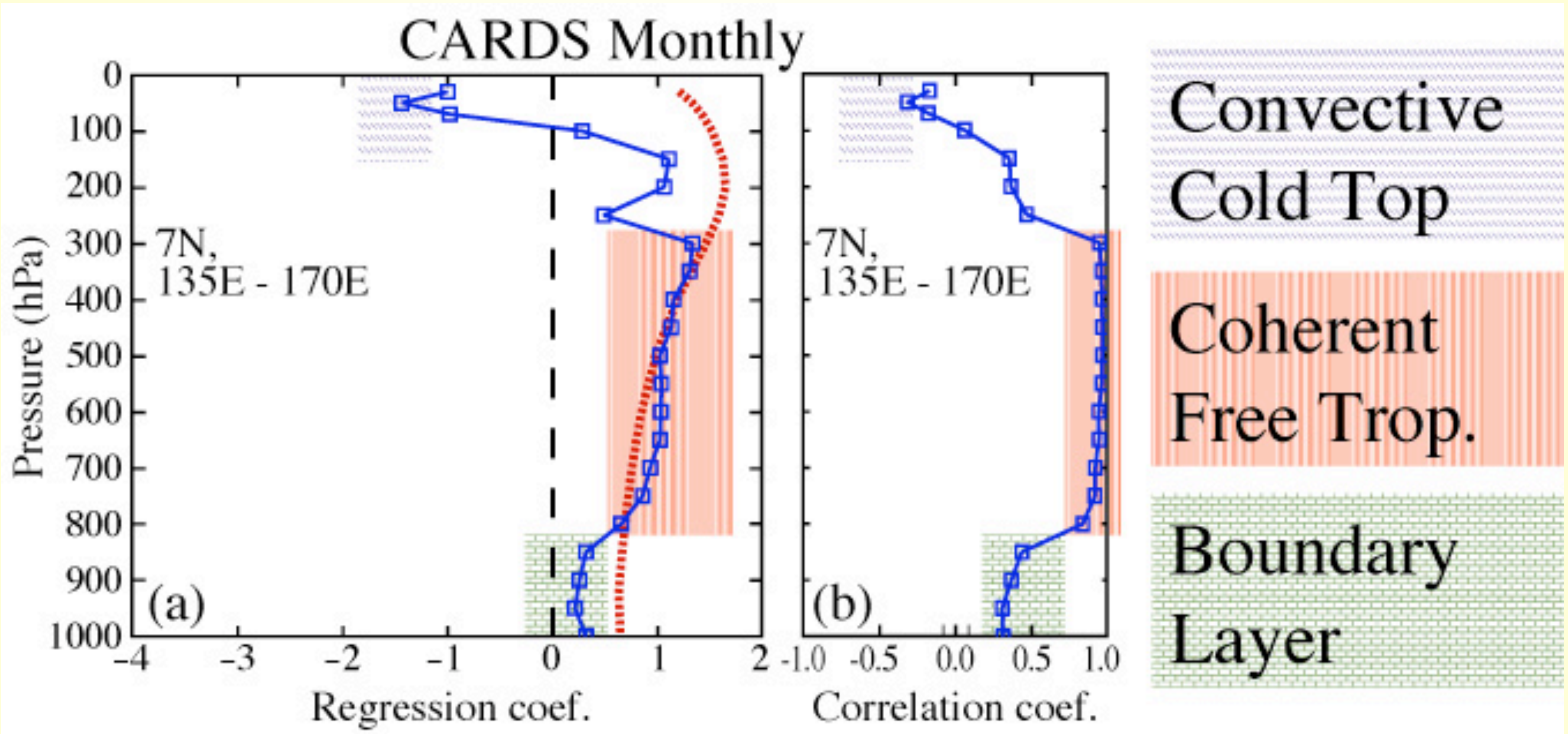
Vertical Temperature structure

(Rawinsondes avgd for 3 trop W Pacific stations)

Monthly T regression coeff. of each level on 850-200mb avg T. **Correlation coeff.**



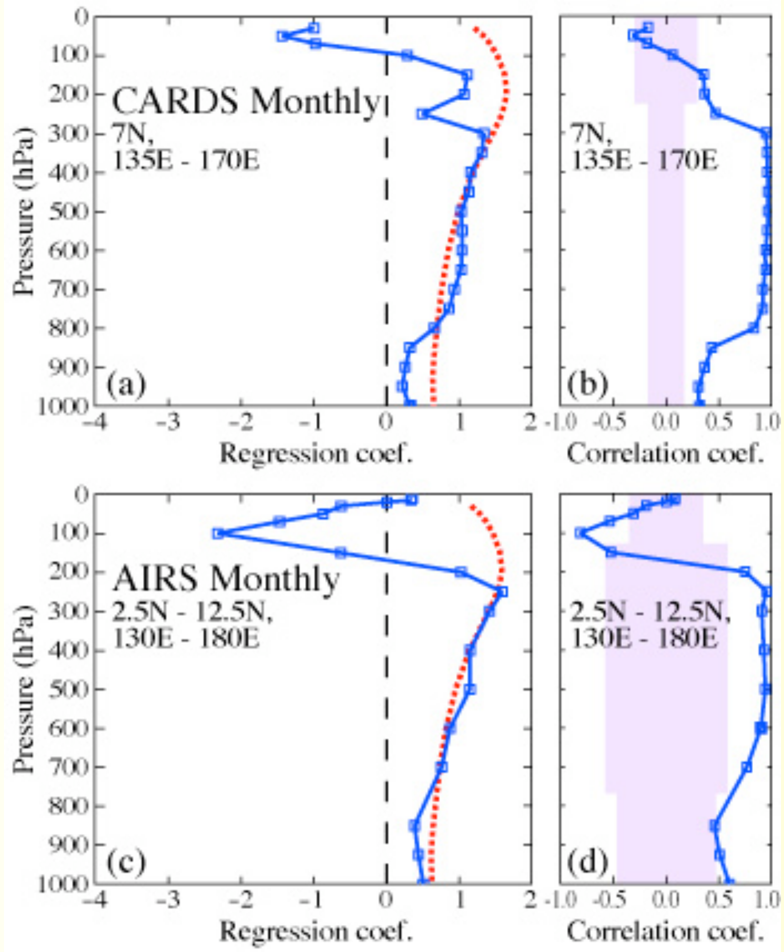
- CARDS monthly 1953-1999 anomalies, shading < 5% signif.
- Curve for moist adiabatic vertical structure in red.

Vertical Temperature structure

Monthly T regression coeff. of each level on 850-200mb avg T.

CARDS
Rawinsondes
avgd for 3 trop Western Pacific stations, 1953-99

AIRS monthly (avg for similar Western Pacific box, 2003-2005)



- shading < 5% signif.
- Curve for moist adiabatic vertical structure in red.

Vertical Temperature structure

(Daily, as function of spatial scale)

AIRS daily T

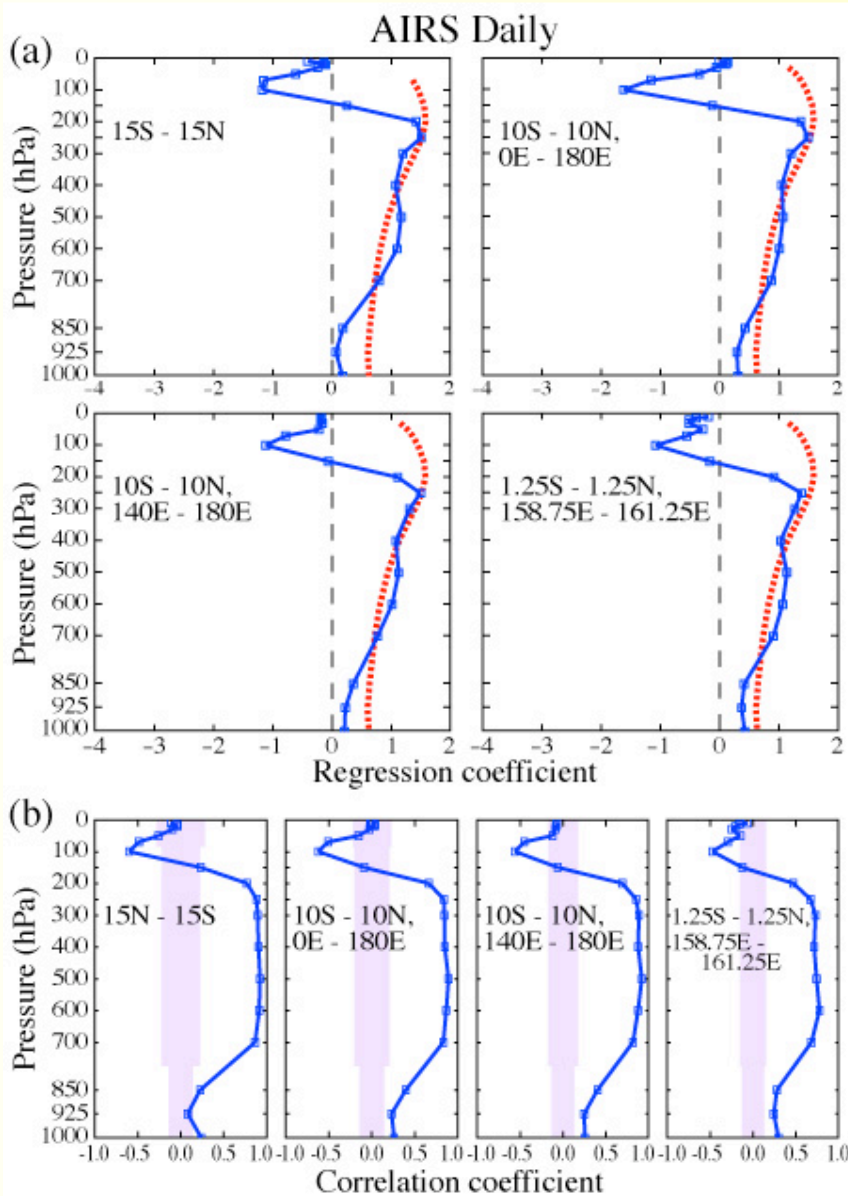
(a) Regression of T at each level on 850-200mb avg T

For 4 spatial averages, from all-tropics to 2.5 degree box

Red curve corresp to moist adiabat.

(b) Correlation of T(p) to 850-200mb avg T

•AIRS level 2 v4 daily avg Nov 2003-Nov 2005

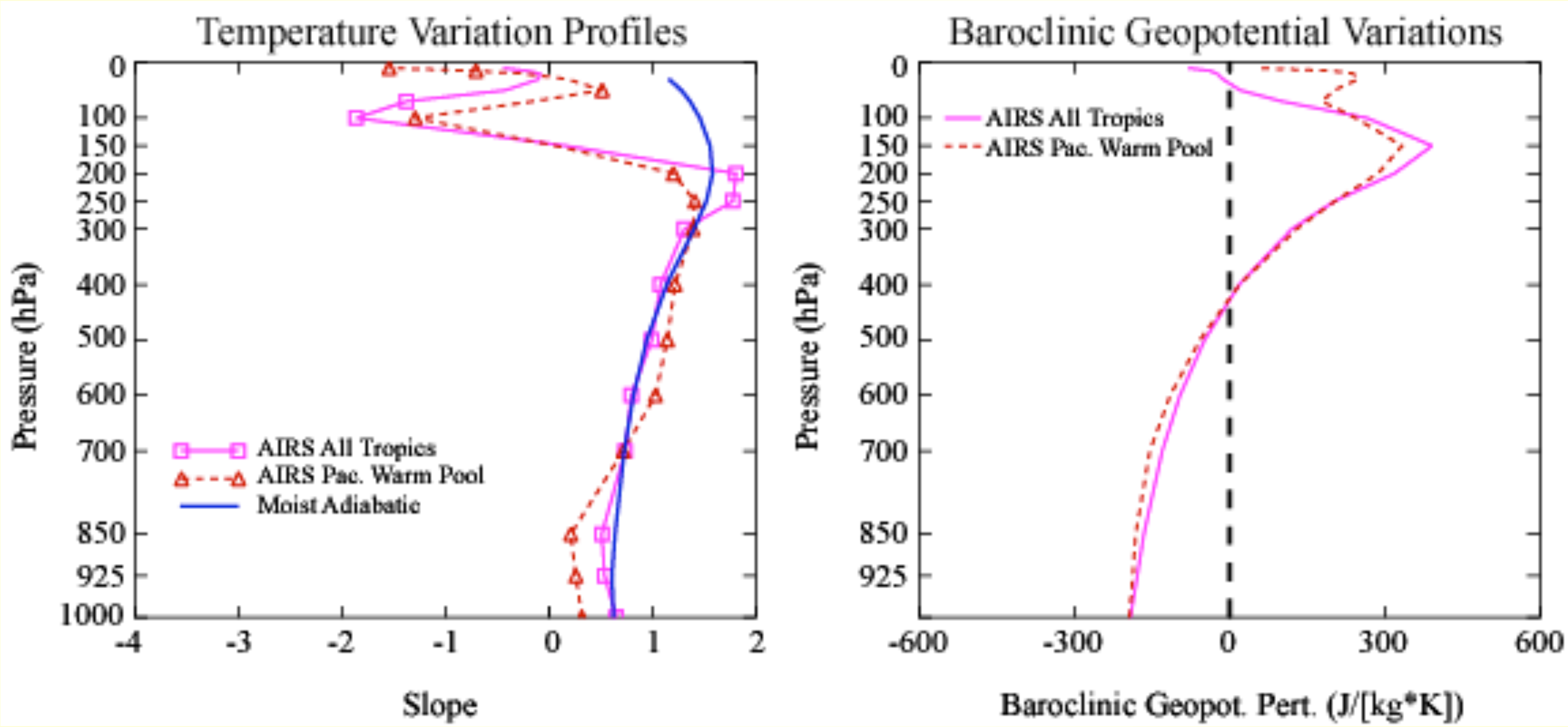


Vertical Temperature structure

(and implied baroclinic geopotential structure)

AIRS daily T regressed on 850-200mb avg T vs. moist adiabat.

Resulting baroclinic geopotential

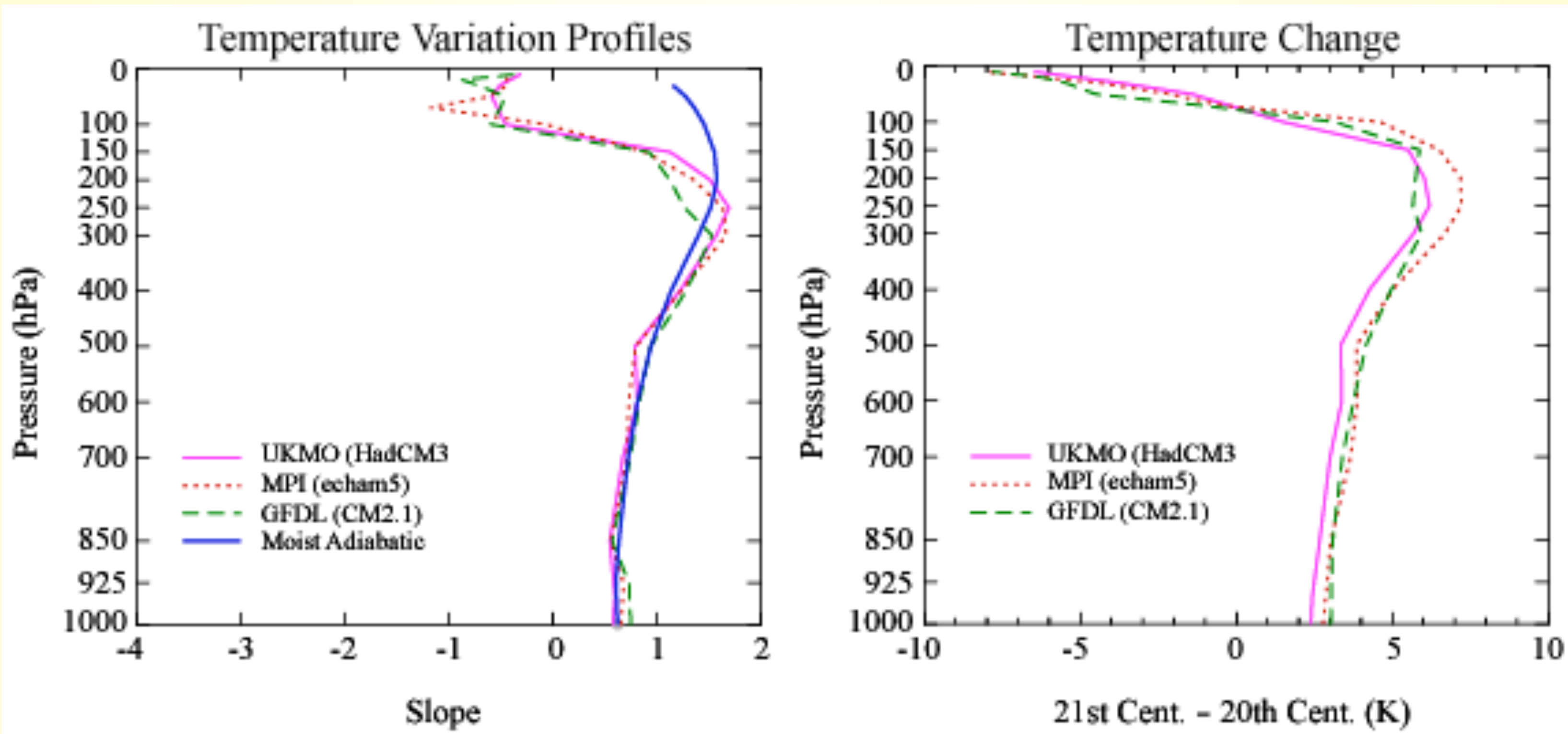


•AIRS level 2 v3 daily avg Jun-Jul 2003, markers signif. at 5%. All tropics = 15S-15N; Pac. Warm pool= 10S-10N, 140-180E.

QE in climate models
(HadCM3, ECHAM5, GFDL CM2.1)

Monthly T anoms regressed on 850-200mb T vs. moist adiabat.

Model global warming T profile response



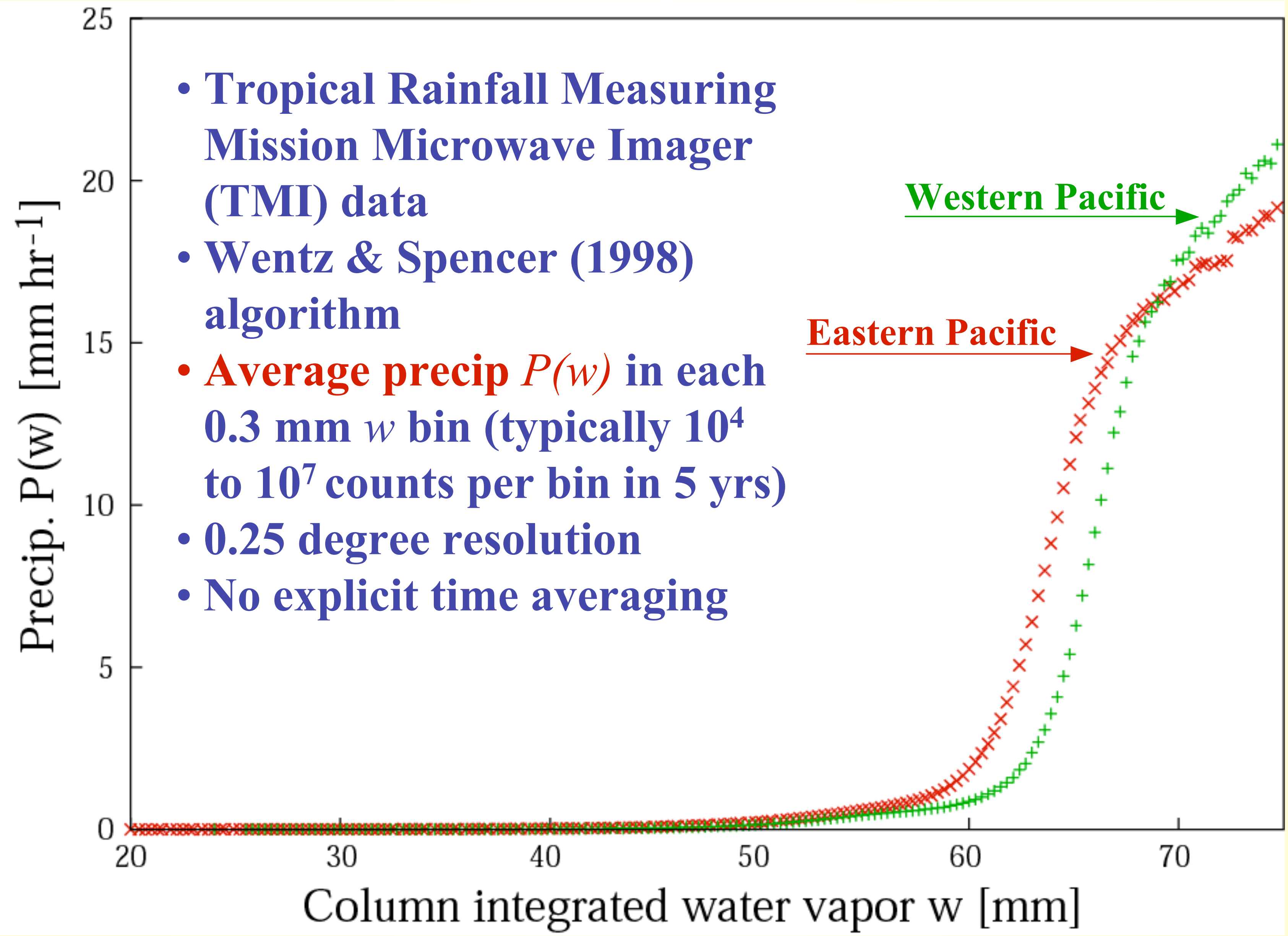
•Regression on 1970-1994 of IPCC AR4 20thC runs, markers signif. at 5%. Pac. Warm pool= 10S-10N, 140-180E. Response to SRES A2 for 2070-2094 minus 1970-1994 (https://esg.llnl.gov)

2. Onset of strong convection regime as a continuous phase transition with critical phenomena

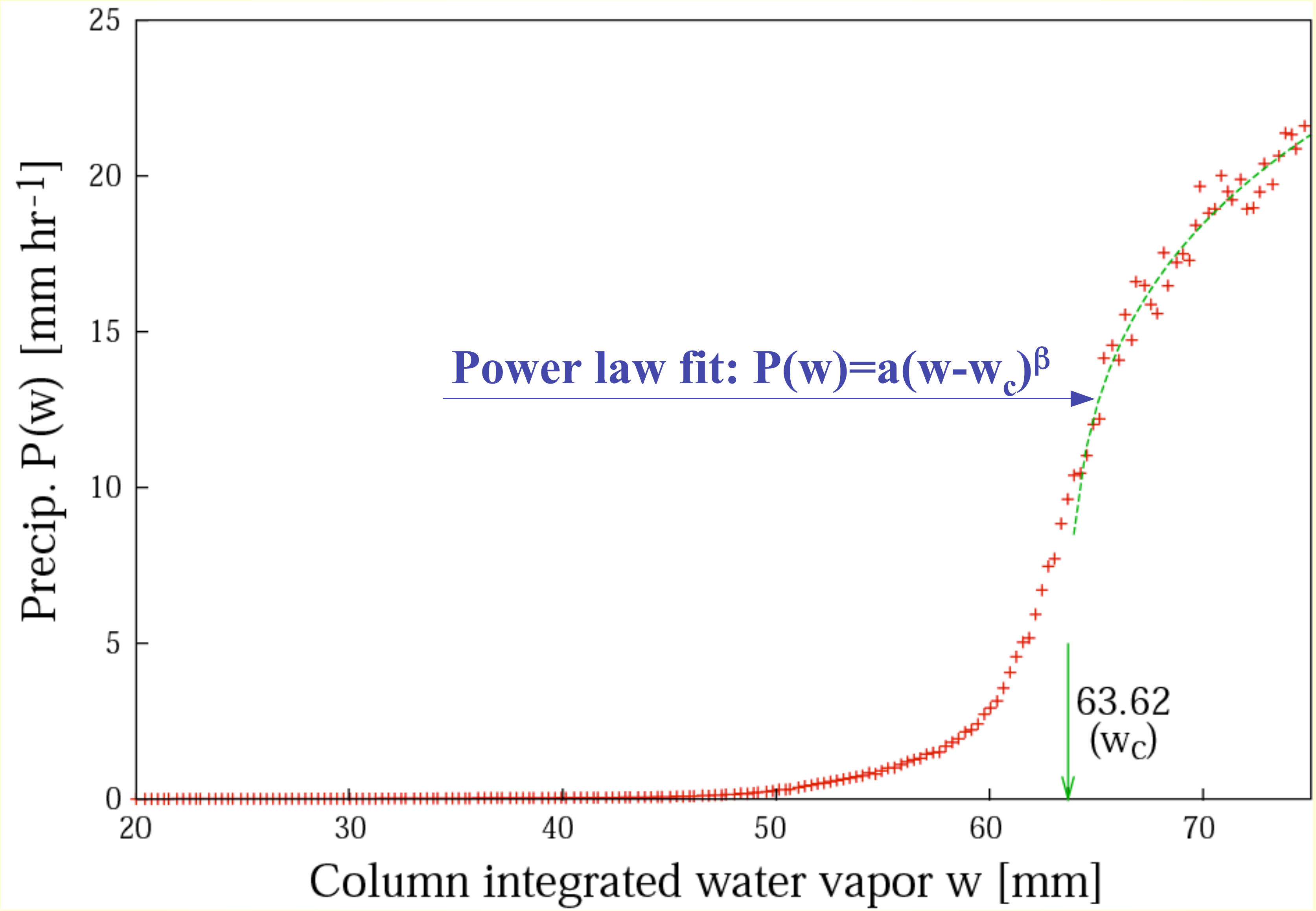
O. Peters & J. D. Neelin, in prep for TBD.

- Background: precip tends to increase with column water vapor at >daily time scales (e.g., Bretherton et al 2004)
- What happens at strong precip? Half of convective events in 6 min. station data are > 20 mm/hr. (Jones & Smith 1978)
- In models, convection onsets when moisture large enough to create conditional instability & buoyant plumes for a given T
- Convective QE postulates sound similar to self-organized criticality postulates, known in stat. mech. models to be assoc. with continuous phase transitions (NB. Not to be confused with the first order phase transition of condensation at microphysical scales)
- Data here: Tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI) water vapor, precip/cloud liquid water from Remote Sensing Systems
- In progress: AMSR-E, TRMM Precip radar (2B31 product)

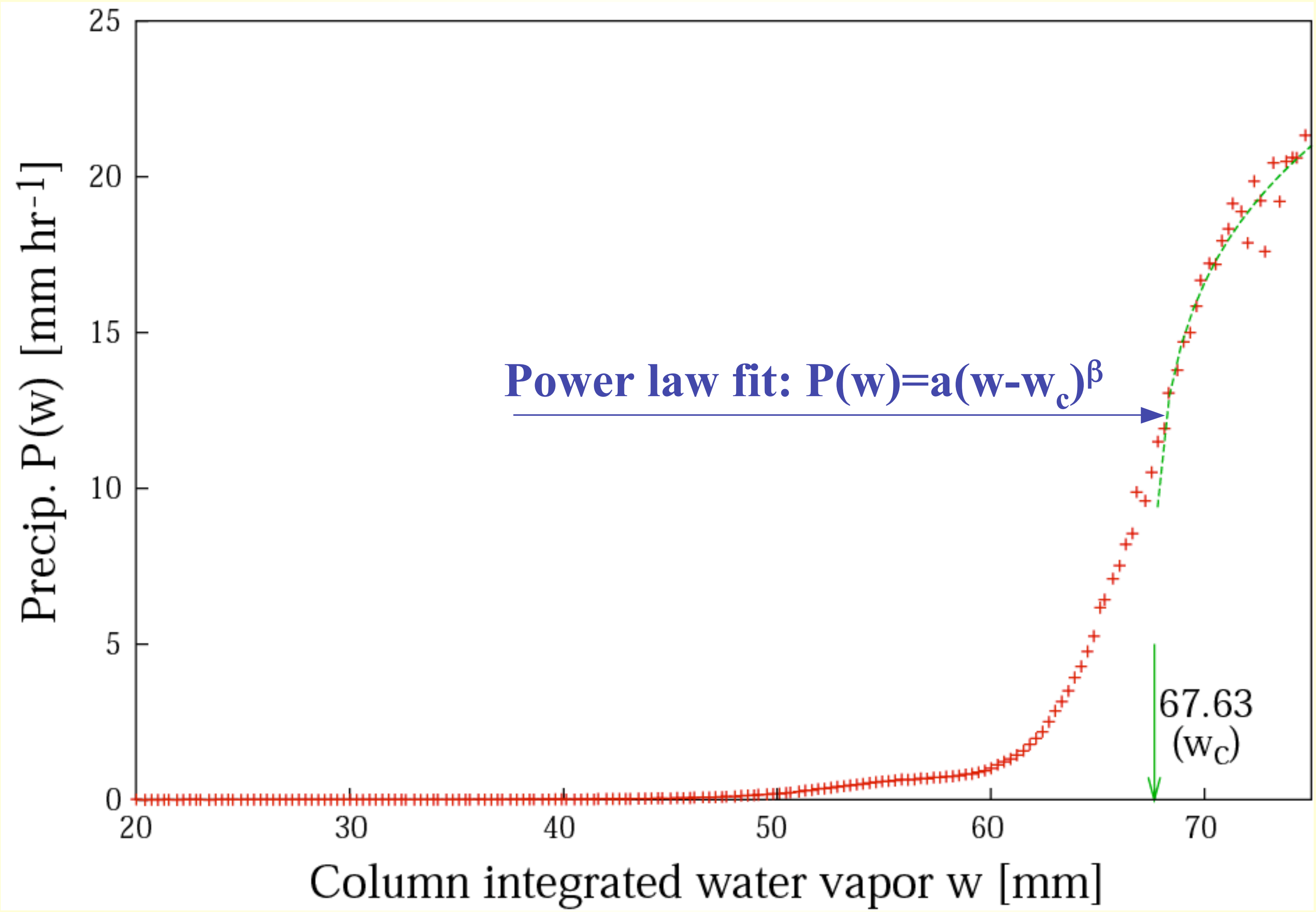
Western Pacific precip vs column water vapor



Indian Ocean for SST within 1C bin at 25C

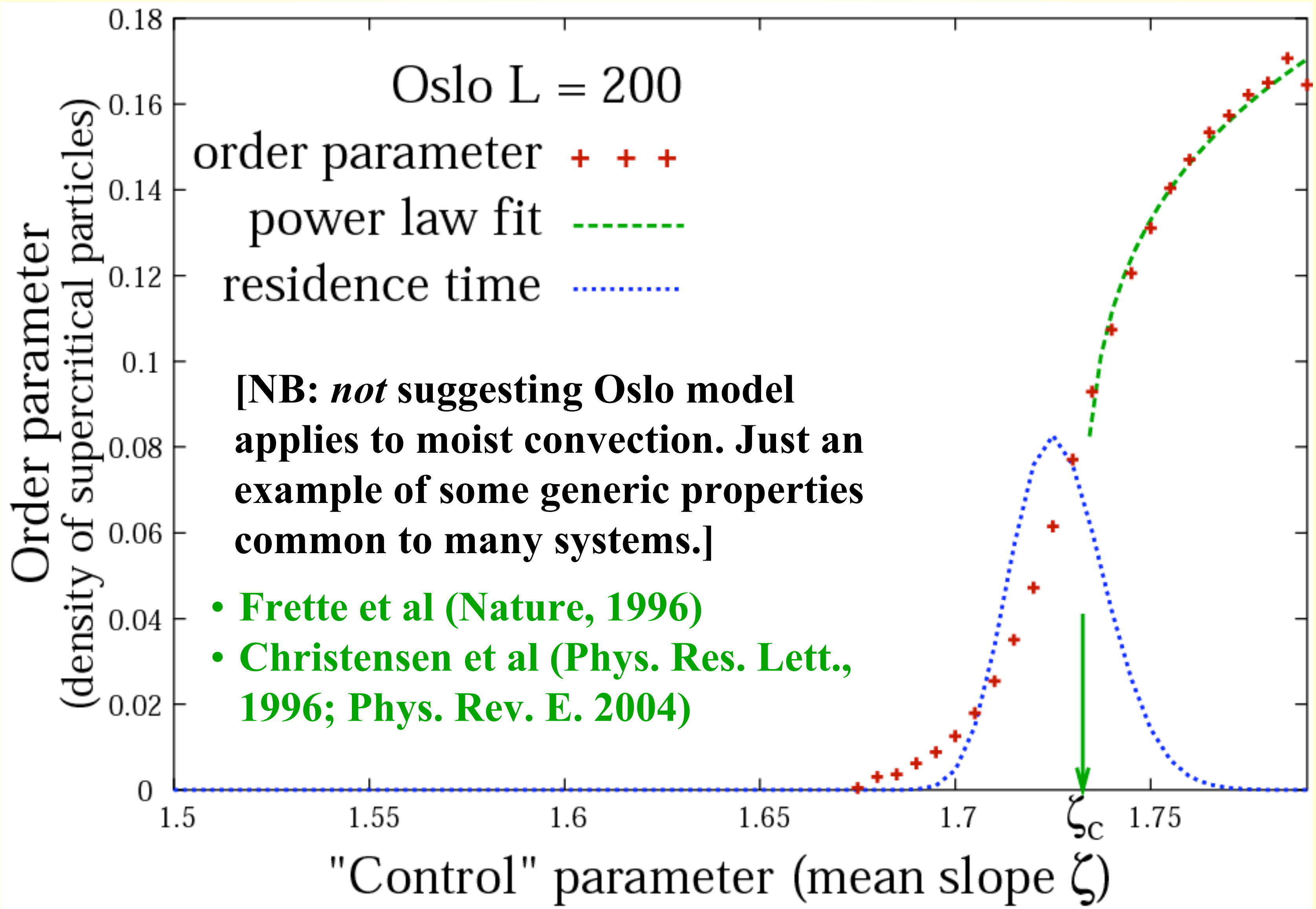


Indian Ocean for SST within 1C bin at 31C



Oslo model

(stochastic lattice model motivated by rice pile avalanches)



[NB: *not* suggesting Oslo model applies to moist convection. Just an example of some generic properties common to many systems.]

- **Frette et al (Nature, 1996)**
- **Christensen et al (Phys. Res. Lett., 1996; Phys. Rev. E. 2004)**

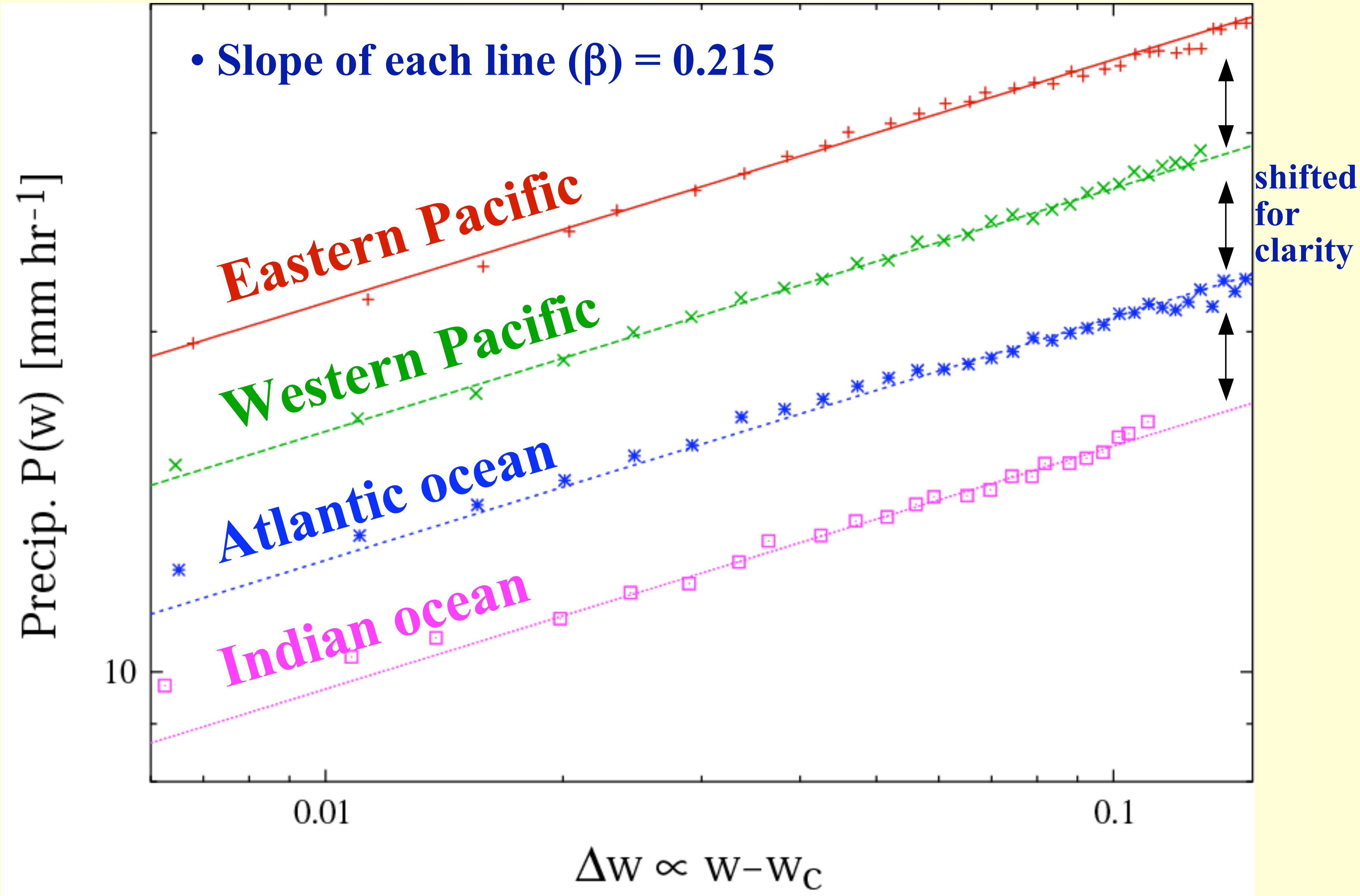
Things to expect from continuous phase transition critical phenomena

- Behavior approaches $P(w) = a(w - w_c)^\beta$ above transition
- exponent β should be robust in different regions, conditions.
  ("universality" for given class of model, variable)
- critical value w_c should depend on other conditions: region, boundary layer T, q (TMI SST as proxy), tropospheric temperature,...
- factor a also non-universal; re-scaling P and w should collapse curves for different regions
- below transition, expect $P(w)$ depends on finite size effects. Spatial avg over length L increases # of degrees of freedom in the average.

Things to expect (cont.)

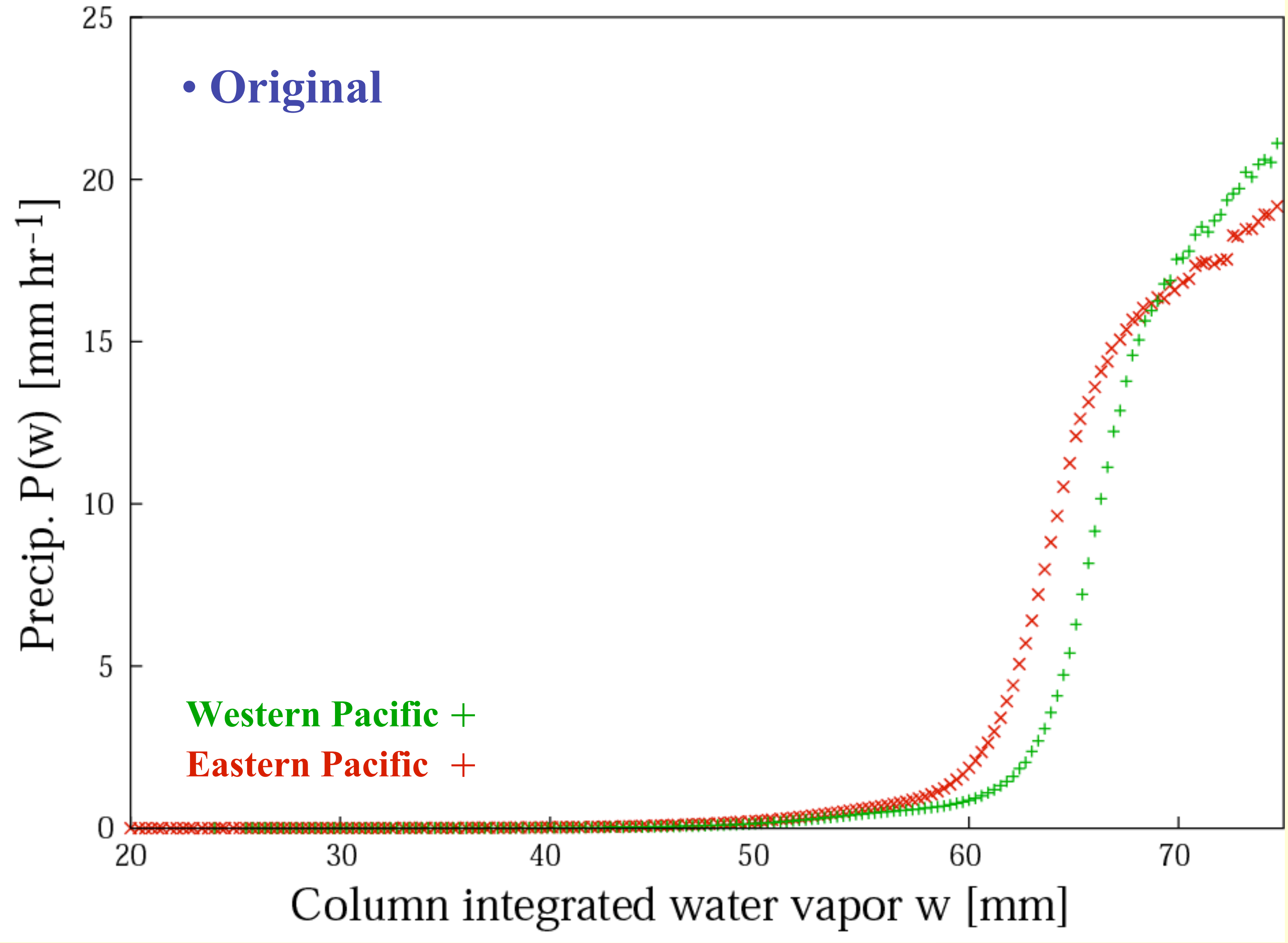
- **Precip variance $\sigma_P(w)$ should become large at critical point.**
- **Expect $L^2\sigma_P(w,L) \propto L^{\gamma/\nu}$ near the critical region**
- **i.e., spatial correlation becomes long (power law) near crit. point**
- **Here check effects of spatial averaging length L. Can one collapse curves for $\sigma_{P(w)}$ in critical region?**
- **correspondence of self-organized criticality in an open (dissipative), slowly driven) system, to the absorbing state phase transition of a corresponding (closed, no drive) system.**
- **frequency of occurrence: expect maximum just below w_c**
- **Refs: e.g., Yeomans (1996; Stat. Mech. of Phase transitions, Oxford UP), Vespignani & Zapperi (Phys. Rev. Lett, 1997), Christensen et al (Phys. Rev. E, 2004)**

log-log Precip. vs ($w-w_c$)



(individual fits to β within ± 0.02)

How well do the curves collapse when rescaled?



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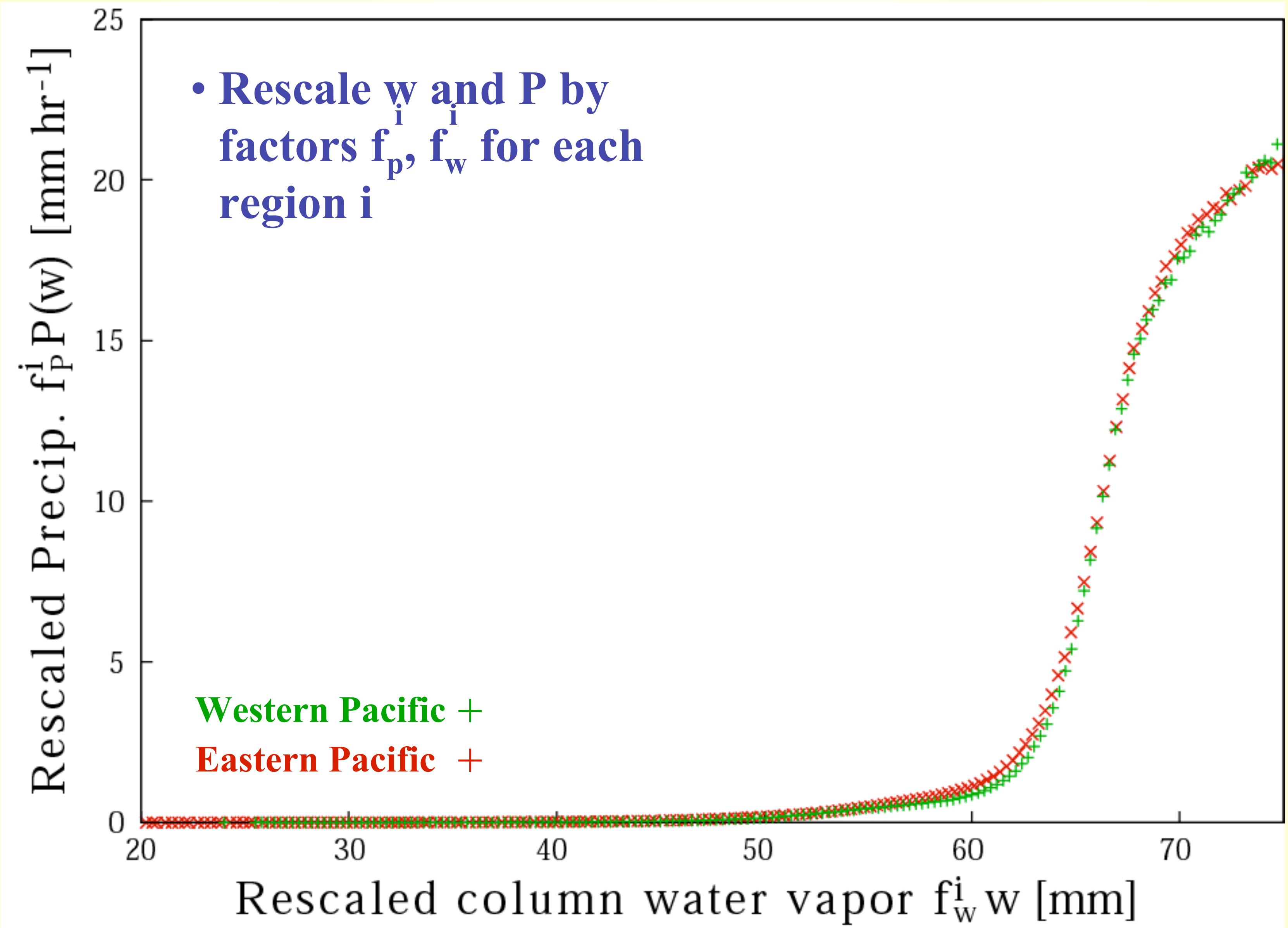
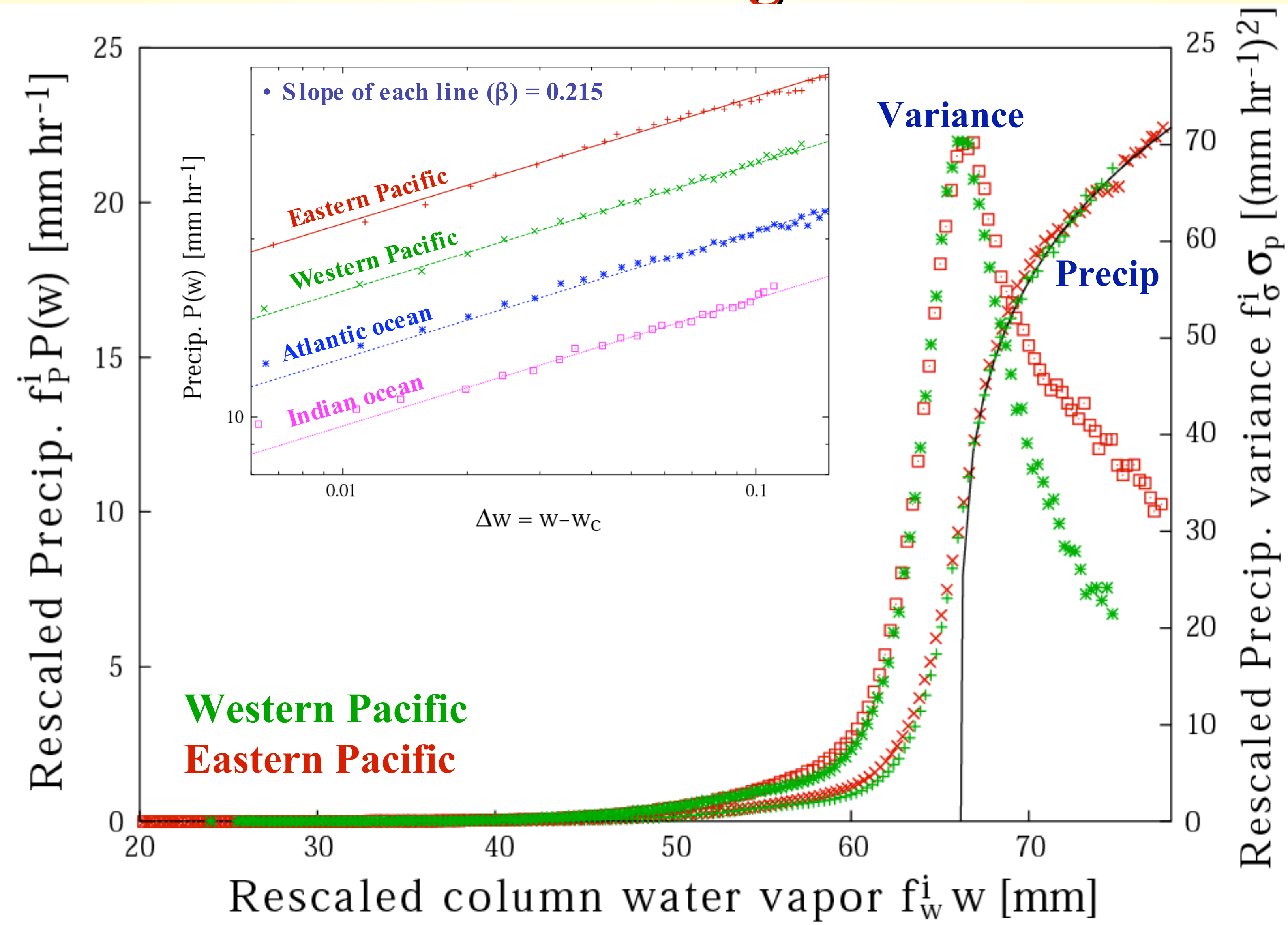
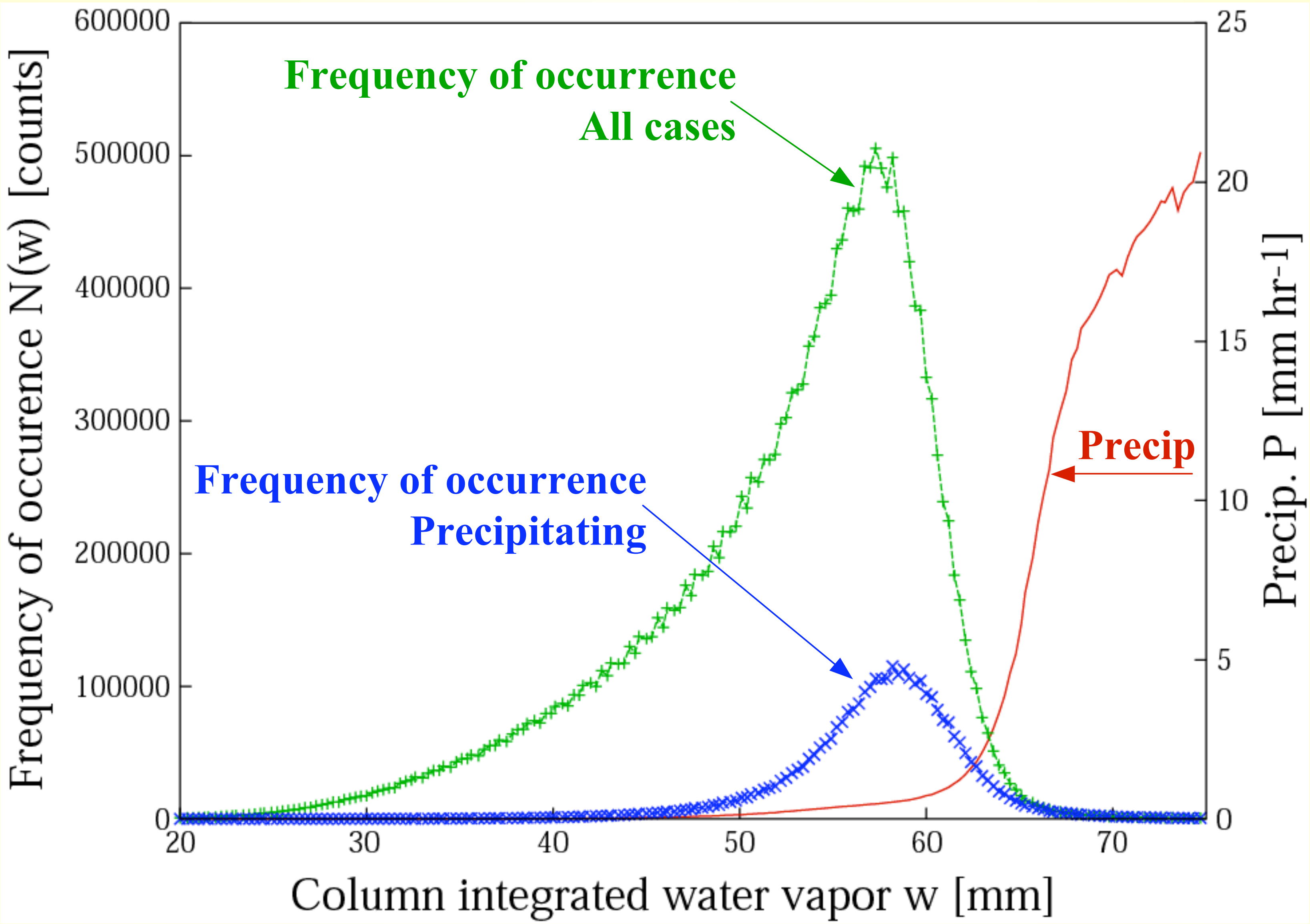


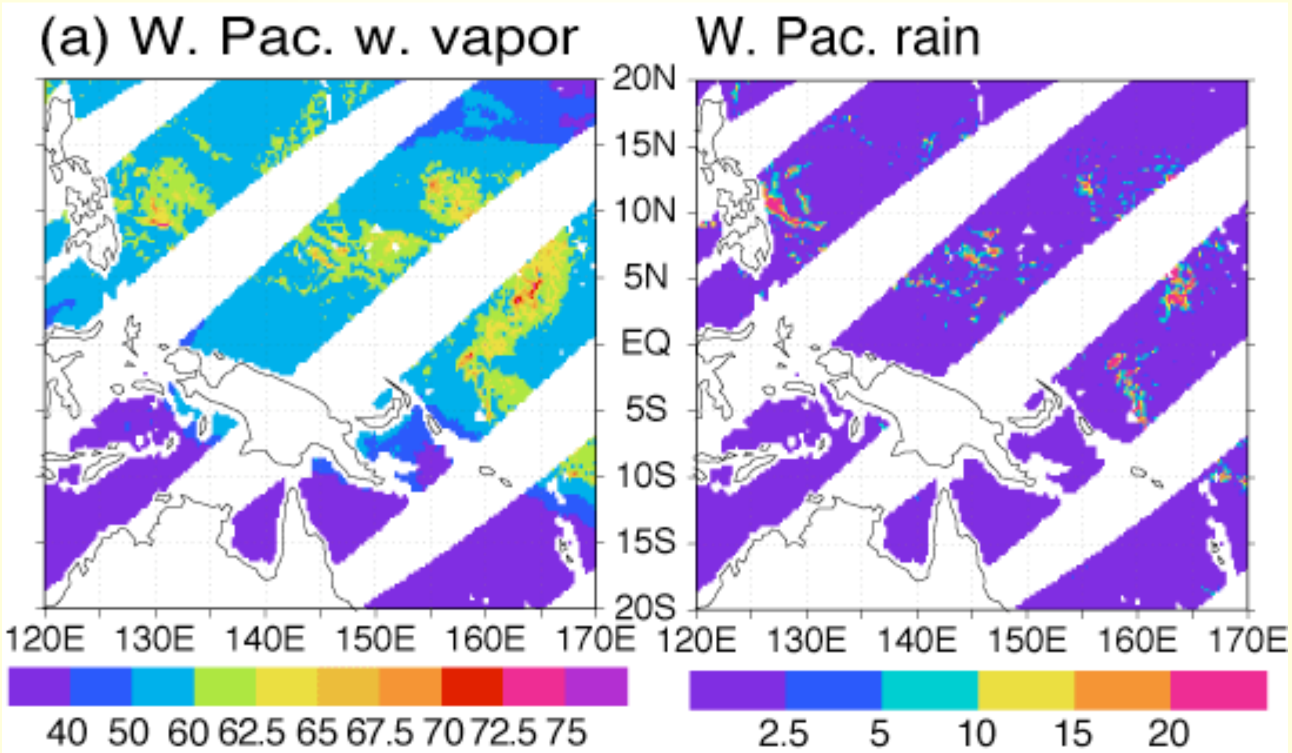
Collapse of Precip. & Precip. variance for different regions



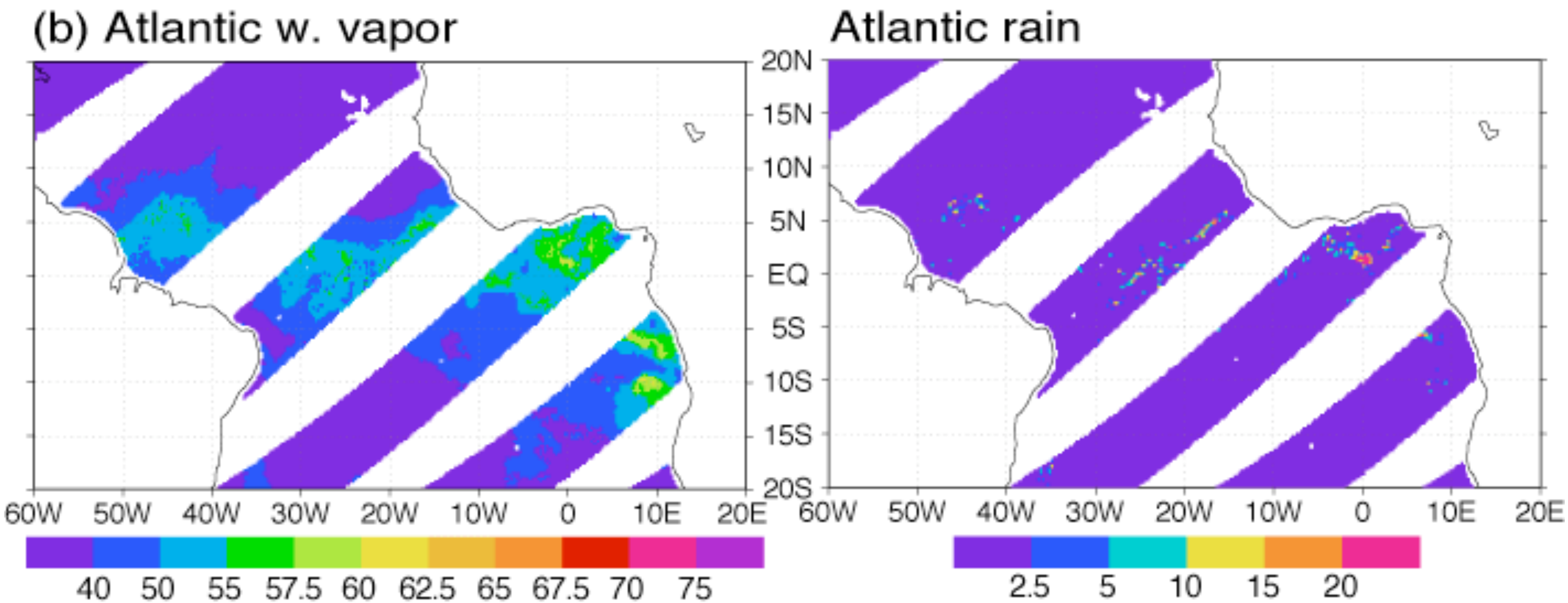
Western Pacific for SST within 1C bin of 30C



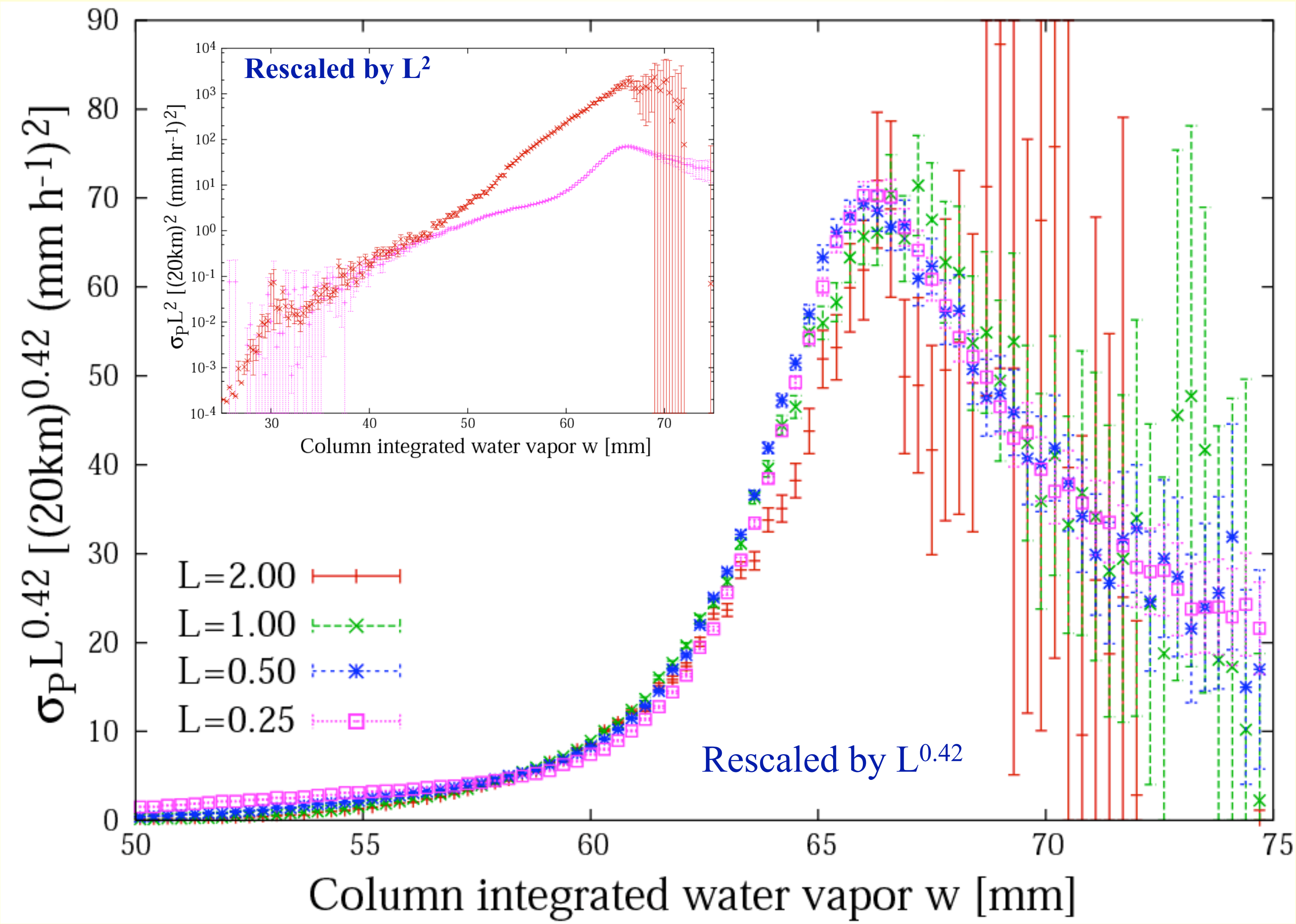
TMI column water vapor and Precipitation
Western Pacific example



TMI column water vapor and Precipitation Atlantic example

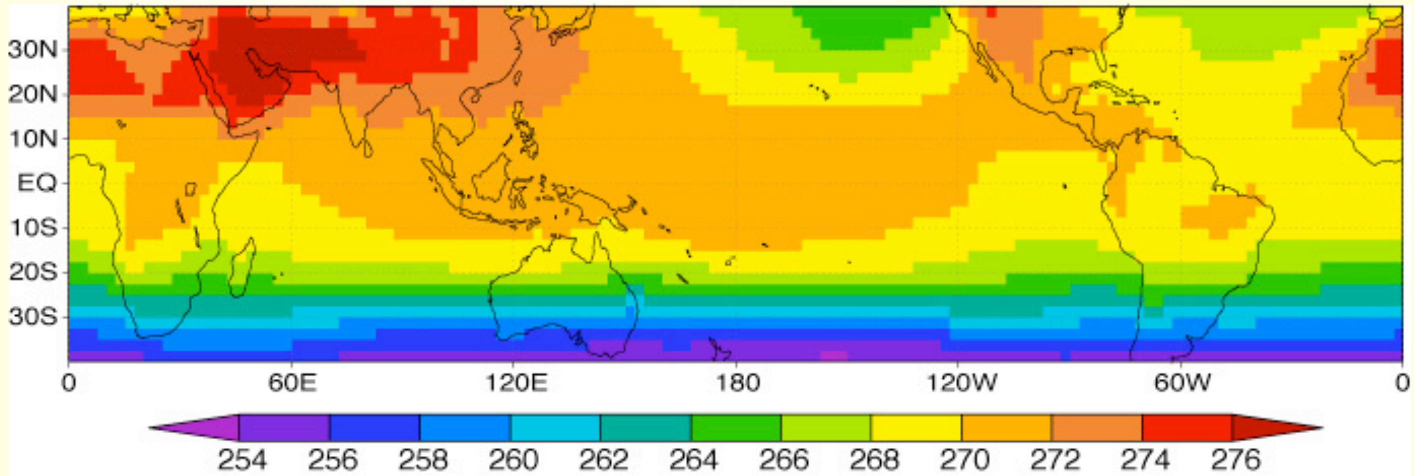


Precip variance collapse for different averaging scales

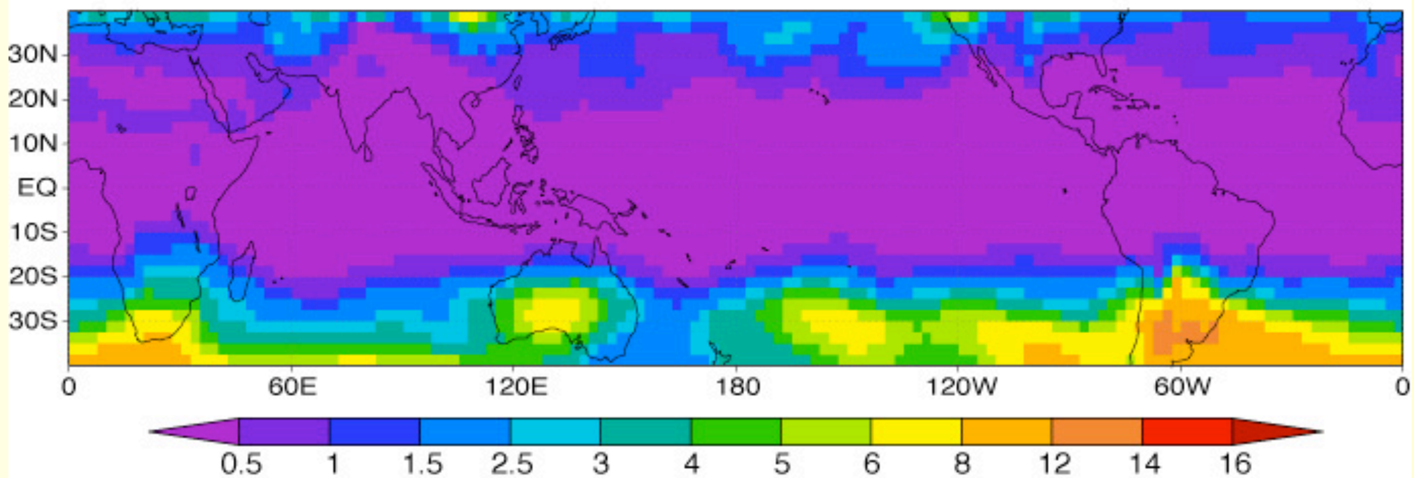


Preliminary: water vapor Precip. relation temperature dependence

Average



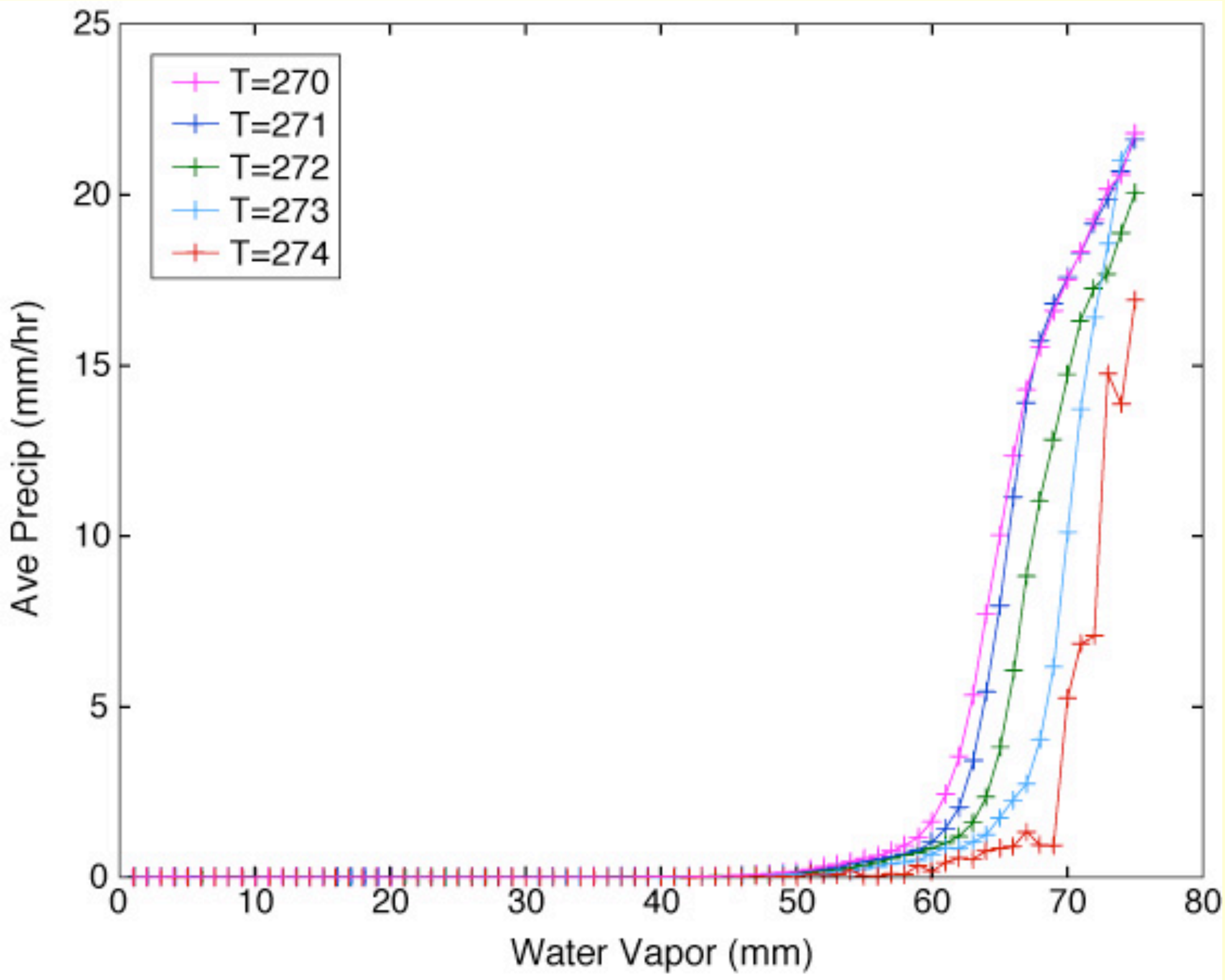
Standard deviation



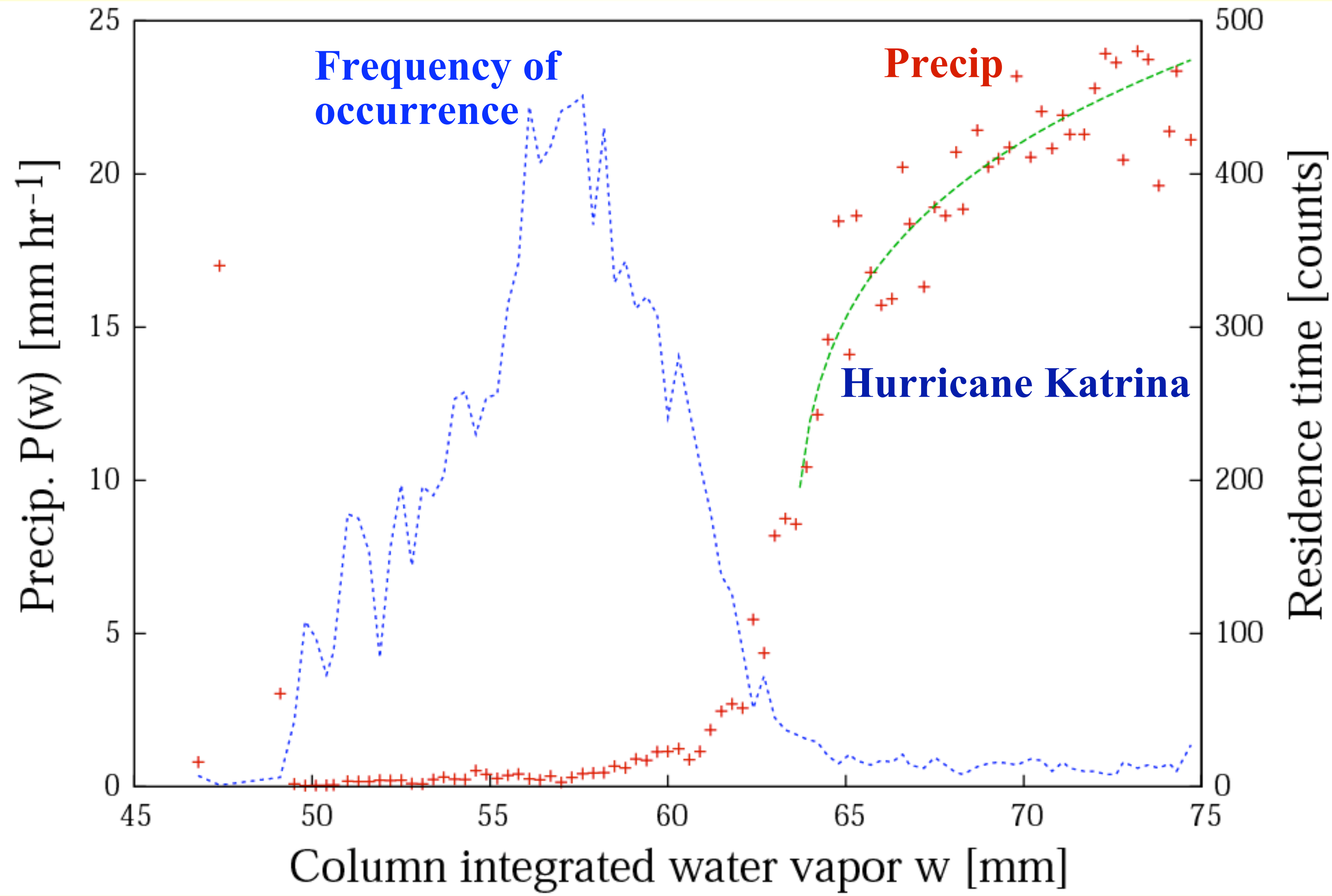
July ERA40 reanalysis daily Temperature: Tropospheric vertical average (1000-200mb)

Dependence of <P(w)> on tropospheric Temp

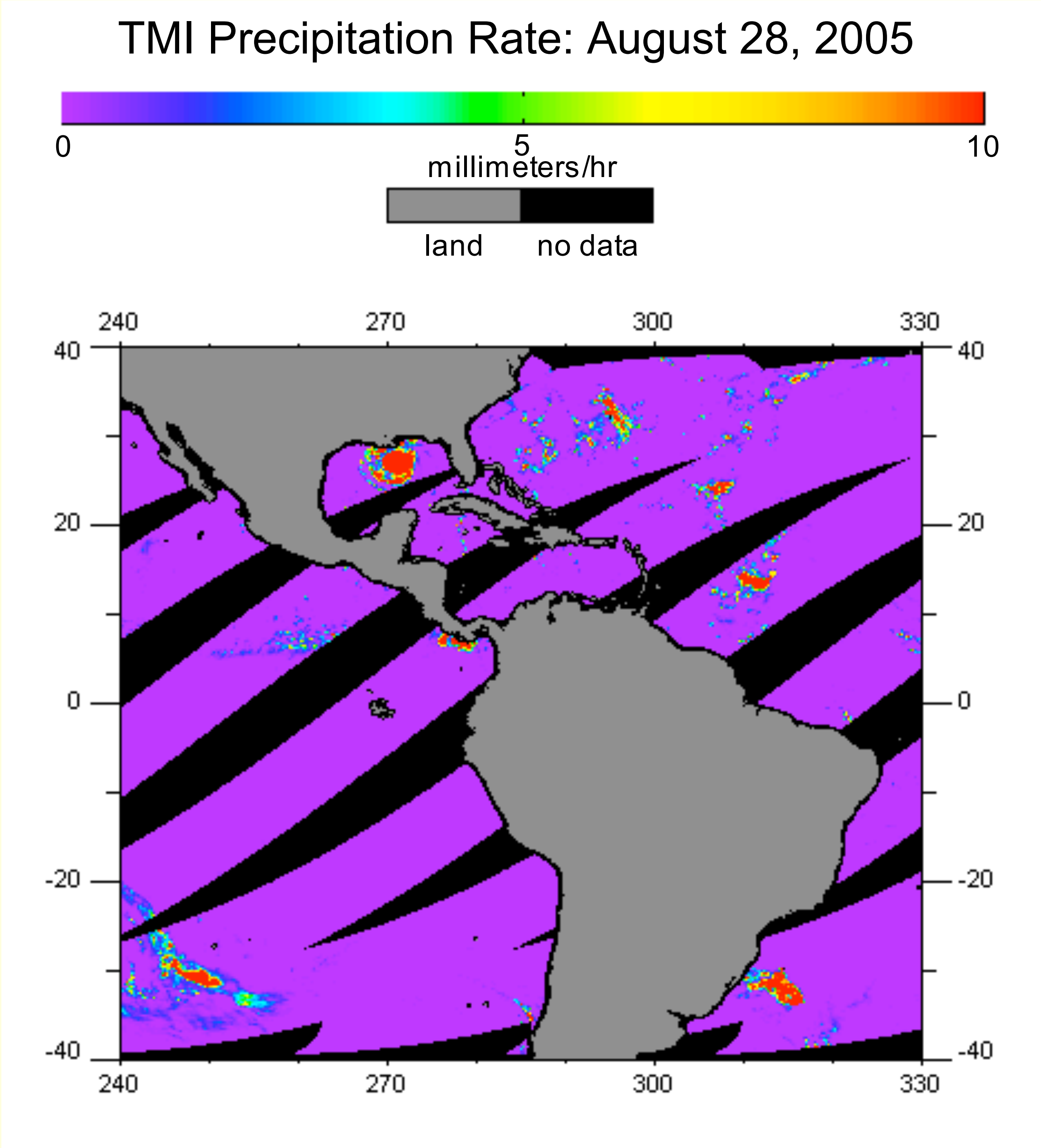
- TMI Precip P, column water vapor w
- ERA40 Reanalysis daily Temp.
- <P(w)> within 1C bins of vertical avg T (1000-200mb)
- critical water vapor value w_c increases with T



How does this relation hold up on smaller ensembles?
Four days over the Gulf of Mexico
Aug. 26 to 29, 2005, 100W-80W



TMI Precip. Rate Aug. 28, 2005 (desc)



Implications

- Transition to strong precipitation in TRMM observations conforms to a number of properties of a continuous phase transition and associated self-organized criticality

- convective quasi-equilibrium assoc with the critical point
- suggests different properties of pathway to critical point than used in convective parameterizations (e.g. not exponential decay; distribution of precip events)
- Suggests: spatial scale-free range in the convective to mesoscale assoc with QE; Mesoscale convective systems like critical clusters in atomic scale phase transitions
- May be able to "map" critical point as fn of tropospheric temp,
- ABL θ_e…

Summary

- Convective quasi-equilibrium (QE) underlies most convective parameterizations in climate models and tropical dynamical theory.
- AIRS (+ other) data: vertical structure of tropical temperature coherent in free troposphere at large scales, consistent with QE
- BUT convective cold top, indep ABL.
- TRMM (so far TMI): onset of strong precipitation as function of column water vapor conforms continuous phase transition properties: ways to test/rethink convective parameterization?
- TBD: TRMM PR, AMSR-E. (Wish list: more temperature, moisture info close to convection; hi-res moisture, time info)